UNIVERSITI PUTRA MALAYSIA

EXPERIMENTAL DETERMINATION OF CREEP FATIGUE LIFE OF 316L STAINLESS STEEL PIPE

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By

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Master of Science

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DEDICATION

Firstly, I would like to thank to Allah Most Gracious, Most Merciful for giving His blessing with this opportunity and protecting me to complete this research and preparation of this thesis. I always pray to Allah s.w.t to give me the strength and strong-minded as fulfill and achieve the research as a part of my life.

Secondly, this thesis is gratefully dedicated to my beloved parents who have been given financial and moral support without they never failed to give attention, never bored and pray for me during my works in finishing my thesis.

Lastly, I would like to express gratitude to all my friends for without them I would not be here and much less finishing the thesis.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

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December 2011

Chairman : Associate Professor Aidy Ali, PhD

Faculty : Engineering

Component of engineering structures operating at high temperature such as jet engine, pressure vessels, nuclear reactors, steam and gas turbine including oil and gas plant are subjected to severe thermal and mechanical loading. One of them is tubular structure which is widely used with extensive usage from domestic to aviation. Thus estimate of life and safety is an essential part of design and use. Since the external surface of structures always in contact with environment and is exposed to weather and crash and also due to imperfection during product fabrication, surface crack may exist. The main purpose of this study was to characterize and examine the relative importance of the mechanisms of creep-fatigue interaction on fatigue life in cylindrical structure at high temperature.

Fatigue tests were carried out with constant amplitude at room temperature and at high temperature for smooth specimen in the finite life region of material. Meanwhile constant load and high temperature as 565^{o}C will be imposed to

specimen for creep test. The nature of the hold period (tensile or compressive) affects fatigue life and the surface crack patterns. Creep-fatigue tests with five minutes holds time at maximum tensile stress were conducted using hourglass specimen ñType 316L stainless steelò at temperatures of 565°C. Optical and scanning electron microscopy will be carried out to characterize metallurgical damage in the understanding of microscopic damage mechanics.

The fatigue behaviors of 316L stainless steel from experimental revealed superior behavior compared to as predicted model but still show good agreement with the model. The variation of creep strain rates is clearly show that the secondary creep obeyed with a power of law relationship as constant increase creep rate till the tertiary stages. Experimental results from high temperature low cycle fatigue test show by increasing the temperature there is a reduction in fatigue life of the material. It reduces the fatigue strength of the material. Therefore, the combination of temperature and loading fatigue serve more damage and life reduction in component. It was also determined that crack initiation and propagation at grain boundaries was accelerated under creep fatigue loading condition. It was found that crack initiation occupied a major portion of the failure life under fatigue and creep-fatigue. Creep failure mechanism predominates after short times (>5 minutes).

Finally, the optical and SEM microscope were employed to capture better picture the quality of microstructure and macrostructure of fracture surface, with tensile hold was caused mixed transgranular (TG) + intergranular (IG) propagation. Crack initiation was also changed to IG by employing a tensile hold which was otherwise TG.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENENTUAN UJIKAJI HAYAT KELESUAN RAYAPAN PADA PAIP KELULI TAHAN KARAT 316L

Oleh

KHAIRUL AZHAR BIN MOHAMMAD

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Pengerusi : Prof. Madya Aidy Ali, PhD

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Komponen struktur teknik beroperasi pada suhu yang tinggi seperti enjin jet, kontena/bejana tekanan, reaktor nuklear, gas turbin dan wap termasuk kilang minyak dan gas mengalami beban terma dan mekanik yang tinggi. Salah satunya adalah struktur berbentuk tiub yang banyak digunakan dengan penggunaan yang luas dari permukaan bumi ke udara. Dengan demikian anggaran hayat dan keselamatan merupakan sebahagian penting dari perancangan dan penggunaan. Sejak permukaan luaran struktur selalu bersentuhan dengan persekitaran dan terdedah pada cuaca dan terkena keretakan dan juga kerana ketidaksempurnaan semasa pembuatan produk, retak permukaan mungkin ada. Tujuan utama dari penelitian ini adalah untuk menggambarkan dan memeriksa kepentingan relatif mekanisme dari interaksi/ hubungan kelesuan-rayapan pada jangkahayat lesu pada struktur silinder pada suhu yang tinggi.

Ujian kelesuan dilakukan dengan amplitud tetap pada suhu bilik dan pada suhu yang tinggi untuk spesimen licin di kawasan hayat komponen. Sementara itu beban tetap

dan suhu yang tinggi pada 565°C akan dikenakan kepada spesimen untuk ujikaji rayapan. Sifat tahan masa (regangan atau mampatan) mempengaruhi hayat kelesuan dan corak permukaan retak. Ujian rayapan-kelesuan dengan tahan masa lima minit pada daya regangan yang maksimum dilakukan dengan menggunakan spesimen balang waktu/jam pasir ñType 316L stainless steelò pada suhu 565°C. Ujian optik dan imbasan mikroskop elektron akan dilaksanakan untuk menggambarkan kerosakan metalurgi dalam memahami mekanik kerosakan mikroskopik.

Perilaku kelesuan pada keluli tahan karat 316L dari eksperimen/ujikaji mendedah-kan kelakuan tinggi berbanding dengan model ramalan namun masih menunjukkan ikatan baik dengan model. Variasi kadar regangan rayapan jelas menunjukkan bahawa creep sekunder mematuhi dengan hubungan kekuatan hukum sebagai peningkatan malar kadar rayapan hingga tahap ketiga. Keputusan kajian/ujikaji dari ujian kelesuan kitaran rendah suhu tinggi menunjukkan peningkatan suhu ada pengurangan dalam hayat kelesuan bahan. Ia mengurangkan kekuatan kelesuan bahan. Dengan demikian, kombinasi dari suhu dan bebanan kelesuan melayani lebih banyak kerosakan dan pengurangan hayat di komponen. Hal itu juga ditentukan bahawa permulaan dan perambatan retak pada sempadan butir dipercepatkan pada keadaan bebanan merayapï kelesuan. Didapati bahawa permulaan retak menduduki sebahagian besar dari kegagalan hayat di bawah kelesuan dan rayapan-kelesuan. Mekanisme rayapan-kelesuan mendominasi selepas masa yang singkat (>5minit).

Akhirnya, mikroskop optik dan imbasan mikroskop electron yang digunakan untuk menangkap gambar yang lebih baik kualiti mikro dan makro struktur permukaan pecah, dengan daya tahan regangan disebabkan campuran penyebaran transgranular (TG) + intergranular (IG). Permulaan retak juga mengubah menjadi IG dengan melaksanakan daya regangan tahan yang dinyatakan TG.

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I certify that a Thesis Examination Committee has met on 2nd December 2011 to conduct the final examination of Khairul Azhar bin Mohammad on his thesis entitled "**Experimental Determination of Creep Fatigue Life of 316L Stainless Steel Pipe**" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of **Master of Science**. The members of the Supervisory Committee were as follows:

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DECLARATION

I declare that the thesis is my original work except for quotations and citation which have been duly acknowledged. I also declare that it has not been previously and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or other institutions.

KHAIRUL AZHAR BIN MOHAMMAD

Date: 2 December 2011

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fatigue test at 565^{0}C for third stage (a) macroscopic surface (b) SEM micrograph (c) discontinuity area enlarged (d) EDX spectrum (e) element composition

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NOMENCLATURES

LIST OF ABBREVIATIONS

H_2S	Hydrogen Sulfide
CO_2	Carbon Dioxide
API	American Petroleum Institute
UV	Ultraviolet
E.R.W	Electric Resistance Welded
HTHP	High Temperature High Pressure
ASTM	American Society for Testing and Materials
SEM	Scanning Electron Microscopy
EDX	Energy Dispersive X-Ray
LCF	Low Cycle Fatigue
HCF	High Cycle Fatigue
S-N	Stress-Life
LDR	Linear Damage Rule
PSB	Persistent Slip Bands
DLDR	The Double Linear Damage Rule
SSC	Small Scale Condition
SS	Steady State Condition
TNBR	Tenaga Nasional Berhad Research
UTS	Ultimate Tensile Stress
AISI	American Iron and Steel Institute
CTOD	Crack Tip Opening Displacement

FSW	Friction Stir Welding
C	Carbon
O	Oxygen
F	Fluorine
Cr	Chromium
Mn	Manganese
Fe	Ferum
Co	Cobalt
Na	Natrium
Cl	Chlorine
Mo	Molybdenum
Si	Silicon
S	Sulphur
Yb	Ytterbium
Au	Gold
wt%	Weight Percentage

NOMENCLATURES

LIST OF SYMBOLS

kN	Kilo Newton
da/dN	Fatigue Crack Growth Rates
ΔK	Stress Intensity Factor
$\Delta\varepsilon_t$	Total Width of the Loop
$\Delta\sigma$	Total Height of the Loop
$\Delta\varepsilon_p$	Plastic Strain Range
$\Delta\varepsilon_e$	Elastic Strain Range
E	Young's Modulus
σ'_f	Fatigue Strength Coefficient
ε'_f	Fatigue Ductility Coefficient
σ_f	True Fracture Strength
ε_f	True Fracture Strain
b	Fatigue Strength Exponent
c	Fatigue Ductility Exponent
T_M	Absolute Melting Temperature
$\dot{\varepsilon}_o$	Strain Rate
σ_c	Applied Stress
T	Temperature
t	Time
A_o	Stress Co-efficient
Q	Thermal Activation Energy of Creep

R	Bolztmannôs Constant
n	Stress Exponent
m	Time Exponent
α	Constant of Order Unity
B	Burgers Vectorôs Magnitude of the Dislocation
μ	Shear Strength
ΔF	Activation Energy
k	Boltzmanôs Constant
$\dot{\tau}$	Flow Stress
σ	Applied Stress
C^*	Time-Dependent Energy Integral
з	Poissonôs ratio
n	The Norton Law Exponent
$C*$	Creep Integral
Γ_s	Counter-clockwise Contour
MPa	Mega Pascal
t_{ht}	Hold Time Period
HCL	Hydrogen Chloride
HNO_3	Nitric Acid
σ_{FL}	Stress of Fatigue Limit

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